Renewable and Sustainable Energy Reviews 13 (2009) 1104–1110

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Wind resource assessment of the Southern Appalachian Ridges in the Southeastern United States

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ARTICLE INFO

Article history:
Received 18 December 2007
Accepted 28 December 2007

Keywords:
Wind
Southern Appalachian Ridges
Southeastern United States

ABSTRACT

The analysis of wind data collected throughout the Southern Appalachian Mountain region of the Southeastern US is presented. Data were collected at 50 m above ground level on nine ridge top sites between 2002 and 2005. Monthly average wind speeds, power densities, wind sheers, and turbulence intensities, along with monthly maximum gusts, are presented. Measured annual average wind speeds are compared to AWS TrueWind predictions. Diurnal variations in wind speed are also reported. Annual wind roses for each site are presented. Annual wind speeds range from 5.5 to 7.4 m/s with the highest annual average wind speeds found on ridges near the northern TN–NC border. A 20% winter and nighttime enhancement of the wind speed was observed. The prevailing wind is from the westerly directions. The estimated annual energy outputs from a small wind farm consisting of fifteen 1.5 MW GE turbines range from 50 to 75 MkWh, and estimated capacity factors range from 25% to 35%. This analysis suggests that ridges in the region are suitable for utility-scale wind development.

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1. Introduction

Wind is the fastest growing energy technology in the world today. Over the past 7 years, annual worldwide growth in installed wind capacity is near 30% (over 94,000 MW installed currently) [1], and over the same period wind power has grown over 20% annually in the US (16,800 MW installed currently) [2]. However, within the 10 Southeastern US states there is one utility-scale wind farm with an installed capacity of 29 MW [3]. An informal analysis of available TrueWinds mesoscale wind resource models of this region indicates that there are approximately 1800 km of ridges with an annual average power

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1364-0321/$ – see front matter
doi:10.1016/j.rser.2007.12.005

density of 400 W/m^2 at 65 m, much of it suitable for utility-scale wind development.

This wind assessment project, conducted jointly by Appalachian State University (ASU) and the Tennessee Valley Authority (TVA) since 2000 [4], has validated the region's wind resources with meteorological monitoring of ridge top sites with utility-scale development potential.

2. History of wind resource assessment in the Southeastern US

The "energy crisis" of the 1970s prompted the US Federal and State governments and utilities to investigate the potential of utility-scale wind. In the early 1980s, the TVA complied a regional wind atlas using wind data from 93 monitoring stations [5] However, most of the stations provided wind speed data at 10 m, and only 11 stations utilized a tower taller than 30 m. Further, only one station was at an elevation greater than 240 m above sea level.

Also in the 1980s, the State of North Carolina monitored wind resources at six mountain sites using 30 m towers. These wind studies were plagued with incomplete data sets and were, because of low tower height, particularly sensitive to turbulence and sheer caused by topography, nearby trees and structures. Between 1979 and 1981, a 2 MW research turbine was successfully operated by the US Department of Energy and the National Air and Space Administration (NASA) on Howard's Knob, in NW North Carolina [6]. Ridge top wind data was collected at 76 m as part of this project. At the time the turbine was the largest in operation in the world.

Pursuit of utility-scale wind began in the late 1990s with TVA's interest in Stone Mountain, TN [7] and later Buffalo Mountain, TN. Quality wind resource assessment began as a result. In 2000, a 2 MW wind farm was built at Buffalo Mountain north of Knoxville, TN [3]. The facility was expanded in 2004 to a total of 29 MW.

In 2000, TVA contracted with AWS TrueWind to provide a low resolution wind map of the TVA service region, including high resolution mapping of four regions in eastern Tennessee with a suspected high wind resource [8]. North Carolina, Virginia, and South Carolina soon followed with publicly funded state-wide high resolution maps in 2001, 2002, and 2005, respectively [9–11].

3. TVA/ASU wind monitoring sites

Wind resource assessment results for nine sites throughout the Southeastern United States are reported in this paper. Results have been previously reported at WindPower 2005 [12] and to the State of Tennessee's Energy Office [13].

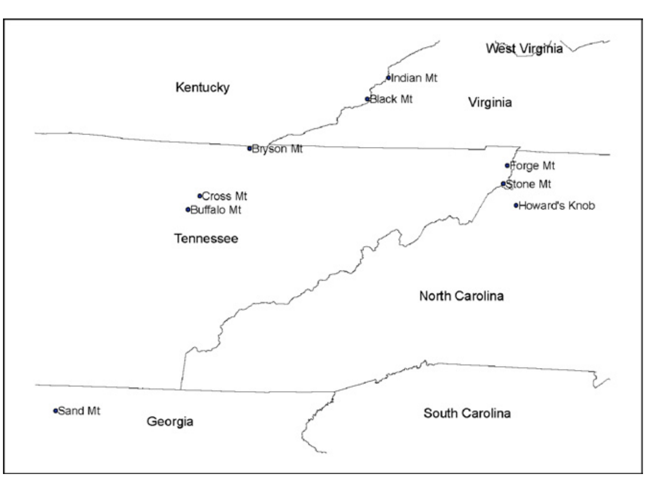

Fig. 1. Location of ASU/TVA wind monitoring sites.

Table 1
Details of ASU/TVA wind monitoring sites

Site	Coordinates	Elevation (m)	Study period
Black Mt, KY	36.91°N, 82.89°W	1250	7/03–4/05
Bryson Mt, TN	36.57°N, 83.83°W	960	11/04–11/05
Buffalo Mt, TN	36.16°N, 84.31°W	1030	1/02–12/03
Cross Mt, TN	36.25°N, 84.22°W	1070	4/02–4/03
Forge Mt, TN	35.90°N, 81.75°W	1250	11/03–12/04
Howard's Knob, NC	36.23°N, 81.68°W	1350	1/77–12/80
Indian Mt, VA	37.05°N, 82.72°W	1100	6/03–4/05
Sand Mt, GA	34.82°N, 85.30°W	500	11/03–9/05
Stone Mt, TN	36.37°N, 81.78°W	1300	4/01–3/02

Regional topography is generally complex, with the Appalachian Mountains and the Cumberland Plateau the dominant features. The Appalachians, a heavily folded chain with peaks to 2000 m, trends SW–NE along the TN–NC border. The Cumberland Plateau, extending from the KY–VA border south through eastern TN, averages 600 m in elevation and contains broad networks of interconnected ridges that reach 1000 m elevation. The northern part of the study region has been extensively strip mined for coal, while the southern extent of the region is largely public land, including the Cherokee and Pisgah National Forests and the Great Smoky Mountains National Park.

The nine sites reported here were selected from candidate sites identified using TrueWinds and topographic maps. Site locations are shown in Fig. 1 with details reported in Table 1. The sites are generally rural ridge tops. The wind sites chosen for observation represent accessible, privately owned sites with utility-scale development potential and a cooperative landowner. These sites are thought to be representative of ridges in the southern Appalachian Mountains; they are not thought to be the best sites.

In addition, a map-based survey of potentially viable utility-scale wind sites within the Cherokee National Forest in eastern TN revealed over 75 km of ridge top with an annual average power density of 400 W/m^2 at 65 m. Other public lands along the TN–NC border likely contain similar resources [13].

4. Instrumentation

Seven of the stations utilized tilt-up 50 m NRG TallTowers instrumented with anemometers at 30, 40, and 50 m, wind vanes at 30 and 50 m, and a thermometer near ground level. The Black Mountain station was a 40 m lattice communication tower, and the Howard's Knob station was a 76 m lattice tower supporting an early 2 MW experimental wind turbine. NRG Systems #40 anemometers, #200P vanes, and #110S temperature sensors were used at all sites except Howard's Knob.

NRG Systems Symphonie or 9300 data loggers were used at all stations except Howard's Knob. At most stations data cards were manually retrieved on a regular basis. The Forge Mountain station had a cell modem that transmitted weekly data files to a host computer.

5. Data collection and analysis procedure

Wind speed, direction, and temperature were sampled at 1 Hz, and 10-min averages were logged (1-h averages were logged at Howard's Knob). Analyses were performed with 10-min averages at all sites except for Howard's Knob. Stations were monitored for at least 1 year. Data from multiple months were combined. Months with less than 20 days of data were excluded from the analysis. Data were manually validated to remove outlier events due to failed instruments, icing, etc. Icing was observed at most sites, and typically 10% of winter data was removed as suspected icing events.

Table 2
Monthly mean and maximum 1 s gust wind speeds and power densities at 50 m (except 40 m at Black Mt and 46 m at Howard's Knob)

	Black Mt			Bryson Mt			Buffalo Mt			Cross Mt			Forge Mt		
	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)
Jan	7.1	29	291	7.7	26	424	7.2	34	427	7.3	33	445	7.4	20	352
Feb	6.0	27	207	8.8	20	530	7.6	35	529	7.5	33	521	7.1	24	382
Mar	6.3	26	201	8.4	30	645	7.6	36	430	6.2	26	238	7.2	29	339
Apr	5.9	24	155	7.1	26	356	7.8	31	431	7.0	29	364	6.8	32	304
May	5.6	26	126	5.3	24	136	6.9	32	319	6.6	(a)	330	5.6	34	150
Jun	4.4	27	70	5.7	12	240	5.1	23	138	5.0	28	124	4.7	30	106
Jul	4.7	24	90	4.7	34	108	4.7	26	90	4.6	24	100	5.0	23	118
Aug	4.2	19	64	4.5	10	76	4.4	23	82	4.6	17	96	4.3	13	66
Sep	5.4	25	166	4.7	15	103	5.6	36	182	5.1	38	145	6.7	35	341
Oct	5.5	26	142	5.6	18	179	5.7	29	224	5.0	30	173	5.3	24	158
Nov	5.7	26	204	6.5	16	284	7.8	36	496	7.2	33	488	6.9	26	340
Dec	7.0	32	322	7.8	24	439	(a)	(a)	(a)	8.1	35	522	7.6	33	424
Annual	5.5	–	156	6.5	–	310	(b)	–	(b)	6.0	–	275	6.1	–	242

	Howard's Knob			Indian Mt			Sand Mt			Stone Mt		
	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)	Mean wind speed (m/s)	Max wind speed (m/s)	Power density (W/m^2)
Jan	8.5	(a)	1327	8.3	26	469	5.2	25	124	8.8	(a)	610
Feb	7.8	(a)	826	7.8	(a)	438	5.0	24	115	9.0	(a)	640
Mar	8.8	(a)	804	6.9	(a)	301	5.2	26	126	8.7	(a)	541
Apr	8.6	(a)	570	7.9	21	377	4.8	25	101	7.7	25	361
May	6.4	(a)	283	6.5	30	219	3.7	17	45	6.8	19	246
Jun	6.5	(a)	368	5.0	25	120	(a)	(a)	(a)	6.2	(a)	205
Jul	6.3	(a)	257	6.4	29	210	(a)	(a)	(a)	6.3	(a)	206
Aug	5.5	(a)	174	4.2	18	75	3.2	29	45	5.3	(a)	132
Sep	5.5	(a)	230	5.7	29	206	3.9	22	58	6.0	(a)	183
Oct	7.4	(a)	450	6.2	29	240	4.3	16	66	8.7	(a)	609
Nov	8.4	(a)	735	7.2	28	380	4.8	21	102	7.2	(a)	354
Dec	7.8	(a)	708	9.0	31	593	5.4	26	138	8.4	(a)	522
Annual	7.2	–	548	6.6	–	276	(b)	–	(b)	7.4	–	372

(a) Data not available. (b) Annual average not calculated due to incomplete data set.

Table 3
A comparison of measured annual average wind speeds to AWS TrueWinds predicted wind speeds at 50 m

Site	Measured (m/s)	TrueWinds (m/s)	Difference (%)
Black Mt, KY*	5.8	7.2	24
Bryson Mt, TN	6.5	6.7	4
Howard's Knob, NC*	7.3	7.0	−4
Buffalo Mt, TN	6.3	6.5	3
Cross Mt, TN	6.0	6.3	5
Forge Mt, TN	6.1	6.5	7
Howard's Knob, NC	7.3	7.0	−4
Indian Mt, VA	6.6	7.0	6
Sand Mt, GA	4.4	4.2	−5
Stone Mt, TN	7.4	7.4	0

*The measured windspeeds at Black Mt and Howard's Knob are sheared up to 50 m.

6. Results and discussion

6.1. Wind speed and power density

Monthly mean and maximum 1 s wind speed gusts at or near 50 m are reported in Table 2. Mean power densities at or near 50 m are also reported. For sites without temperature data, power density was calculated using monthly temperatures obtained from nearby monitoring stations and adjusted for elevation. The annual averages are simple averages of the 12 monthly values.

Of the nine sites, Howard's Knob and Stone Mt appears to be Class 4, while Bryson Mt, Indian Mt, and Buffalo Mt appear to be Class 3. All sites exhibit a significant decrease in summer winds, with typical summer power densities five times lower than typical winter power densities. Gusts of 25 m/s should be expected throughout the year at all sites. The Howard's Knob site is suspected to be particularly gusty, explaining the exceptionally high power densities at that site.

Measured annual average wind speeds are compared to the AWS TrueWind model in Table 3. The predicted 50 m annual average wind speeds agree with the measured value to within 7% at eight of the sites, consistent with TrueWinds reported 7% uncertainty.

Uncertainty in the measured wind speed is dominated by long-term variability. The uncertainty due to year-to-year variability has been estimated by calculating the average of the differences between replicate monthly average 50 m wind speeds at sites where more than 1 year of data were collected. For a sample size of 44, the average monthly difference was 15%, or around twice the difference between measured and predicted wind speeds.

6.2. Turbulence intensity

The turbulence intensity is defined as

$$\mathrm{TI} = \frac{\sigma}{v_{\mathrm{avg}}}$$

where σ is the standard deviation of the 1 s samples contained in each 10 min average wind speed v_{avg}. Turbulence intensity was calculated for the 50 m anemometer, and monthly values are reported in Table 4. The annual average turbulence intensities were below 0.17 except at Black Mt and Howard's Knob. No significant seasonal variation in turbulence intensity was observed.

Table 4
Monthly turbulence intensity at 50 m, 30 m/50 m wind shear α, and Weibull shape parameter k at 50 m [except Black Mt (40 m and 20 m/40 m) and Howard's Knob (46 m and 18 m/46 m)]

	Black Mt			Bryson Mt			Buffalo Mt			Cross Mt			Forge Mt		
	TI	α	k	TI	α	k	TI	α	k	TI	α	k	TI	α	k
Jan	0.19	0.27	2.6	0.16	0.14	(a)	0.16	0.16	(a)	0.17	0.23	1.9	0.15	0.24	2.8
Feb	0.19	0.23	2.2	0.17	0.31	(a)	0.16	0.17	(a)	0.16	0.22	1.8	0.15	0.30	2.1
Mar	0.21	0.26	2.6	0.16	0.12	(a)	0.17	0.18	(a)	0.17	0.17	2.1	0.15	0.28	2.6
Apr	0.21	0.25	2.8	0.15	0.13	(a)	0.14	0.23	(a)	0.17	0.14	2.0	0.16	0.30	2.3
May	0.20	0.25	3.3	0.14	0.17	(a)	0.18	0.22	(a)	0.16	0.20	1.8	0.15	0.24	2.6
Jun	0.18	0.25	2.6	0.12	0.16	(a)	0.17	0.20	(a)	0.14	0.22	2.1	0.15	0.29	2.0
Jul	0.20	0.24	2.4	0.14	0.14	(a)	0.17	0.16	(a)	0.14	0.25	2.0	0.15	0.34	2.1
Aug	0.19	0.17	2.4	0.16	0.13	(a)	0.16	0.15	(a)	0.13	0.22	2.1	0.14	0.22	2.6
Sep	0.17	0.23	1.9	0.13	0.16	(a)	0.15	0.15	(a)	0.15	0.20	1.9	0.15	0.31	1.9
Oct	0.19	0.22	2.3	0.13	0.19	(a)	0.16	0.18	(a)	0.15	0.22	1.6	0.15	0.21	2.0
Nov	0.17	0.23	1.9	0.17	0.15	(a)	0.15	0.11	(a)	0.16	0.20	1.7	0.13	0.27	2.1
Dec	0.18	0.22	2.1	0.16	0.18	(a)	(a)	(a)	(a)	0.15	0.22	2.2	0.14	0.25	2.4
Annual	0.19	0.23	2.4	0.15	0.18	(b)	(b)	(b)	(b)	0.16	0.21	1.9	0.15	0.27	2.3

	Howard's Knob				Indian Mt			Sand Mt			Stone Mt		
	TI	α	k		TI	α	k	TI	α	k	TI	α	k
Jan	(a)	0.18	2.0	(a)	0.17	0.15	2.6	0.18	0.50	2.3	0.14	0.28	2.5
Feb	(a)	0.03	2.1	(a)	0.16	0.08	2.1	0.18	0.51	2.6	0.14	0.30	2.5
Mar	(a)	0.16	1.9	(a)	0.18	0.07	2.2	0.19	0.53	2.7	0.14	0.27	2.5
Apr	(a)	0.24	2.2	(a)	0.18	0.11	2.8	0.19	0.60	3.0	0.13	0.27	2.8
May	(a)	0.22	2.2	(a)	0.18	0.15	2.7	0.19	0.65	2.7	0.13	0.29	2.8
Jun	(a)	0.27	2.0	(a)	0.18	0.12	2.1	(a)	(a)	(a)	0.14	0.29	4.4
Jul	(a)	0.27	2.0	(a)	0.19	0.20	2.8	(a)	(a)	(a)	0.14	0.31	2.6
Aug	(a)	0.30	2.2	(a)	0.19	0.16	2.0	0.18	(a)	2.3	0.14	0.26	2.3
Sep	(a)	0.35	1.9	(a)	0.17	0.17	1.9	0.19	(a)	2.1	0.13	0.27	2.4
Oct	(a)	0.29	2.2	(a)	0.17	0.17	2.1	0.17	(a)	2.5	0.14	0.29	2.3
Nov	(a)	0.29	2.2	(a)	0.16	0.14	2.0	0.19	0.57	2.3	0.14	0.24	2.1
Dec	(a)	0.24	1.8	(a)	0.15	0.14	2.6	0.17	0.51	2.8	0.14	0.26	2.5
Annual	(b)	0.24	2.1	(b)	0.17	0.14	2.3	(b)	(b)	(b)	0.14	0.28	2.6

(a) Data not available. (b) Annual average not calculated due to incomplete data set.

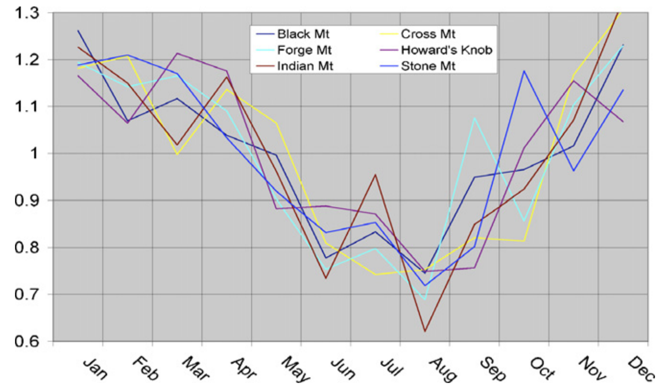

Fig. 2. Variations in the monthly 50 m mean wind speeds normalized to the annual mean wind speed.

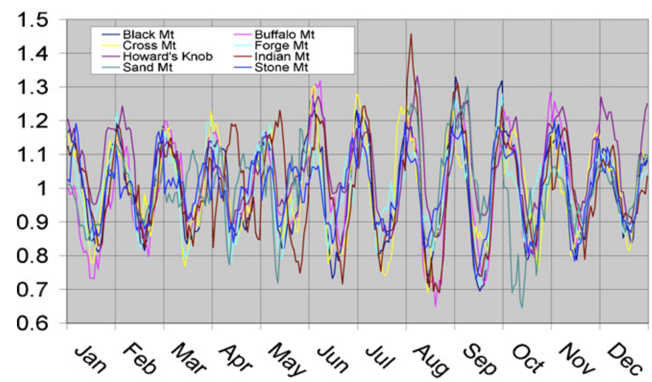

Fig. 3. Variations in the diurnal 50 m mean wind speeds normalized to the respective monthly average wind speeds.

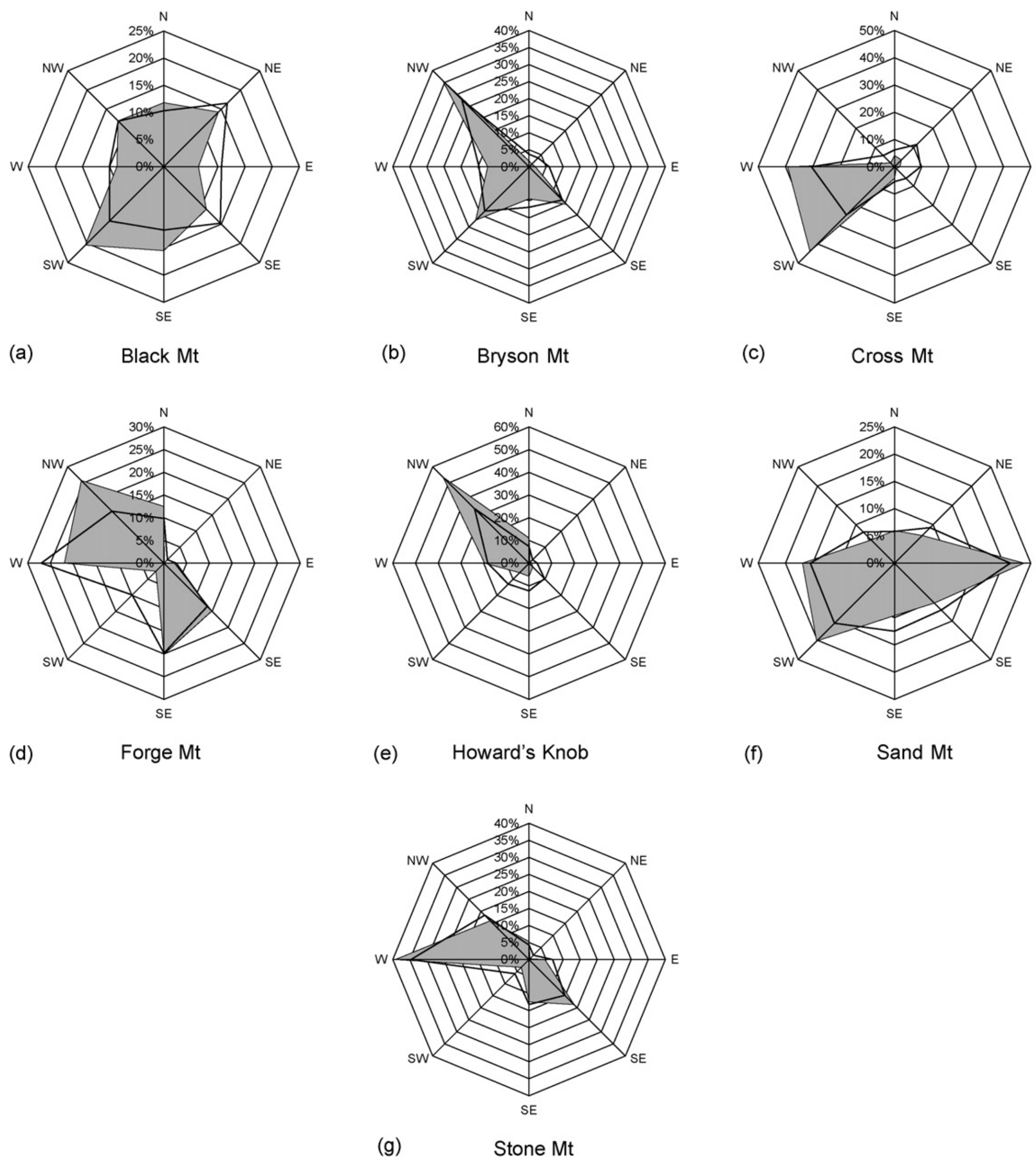

Fig. 4. Wind roses showing prevailing wind direction (outlined rose) and power direction (shaded rose).

6.3. Wind shear

A monthly wind shear coefficient, or wind gradient exponent, α, defined by

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}$$

was calculated for each site, and are reported in Table 4. The wind shear between 30 and 50 m is reported for all sites except Black Mt (20 m/40 m) and Howard's Knob (18 m/46 m).

Wind shears between 30 and 50 m were typically between 0.20 and 0.30, consistent with the complex terrain of the Southern Appalachian Mountains, and higher than the nominal 1/7 value. No significant seasonal variation in wind shear was observed. The Sand Mt site, located near a golf course, exhibited an unexpectedly high shear of 0.5, perhaps due to the mountain's broad top and shallow gradient. The Indian Mt site, located in a coal surface mine, exhibited an expectedly low shear of 0.14. A tall tower program is ongoing to investigate wind sheer in the region up to 100 m [14].

6.4. Wind speed frequency distribution

The Wiebull shape parameter k was calculated using the energy pattern factor K_e from

$$K_e = \frac{(v^3)_{avg}}{(v_{avg})^3} = \frac{\Gamma(1+(3/k))}{\Gamma(1+(1/k))}$$

where Γ is the usual Gamma function [15]. Results at 50 m are reported in Table 4. Shape parameters here are typically in the 2.0–2.5 range, indicating a distribution slightly shifted toward higher wind speeds compared to the traditionally assumed Raleigh ($k = 2$) distribution. No seasonal variation is seen in the shape parameter.

6.5. Monthly and diurnal patterns

The variations of monthly wind speeds at or near 50 m are shown for six sites in Fig. 2. In the figure, each site's monthly average wind speed values are normalized to the respective annual mean wind speed. A strong monthly correlation is seen, with a 20% winter enhancement and corresponding 20% summer reduction in monthly mean wind speed consistently found throughout the region.

The diurnal variations of mean wind speeds at or near 50 m are shown for eight sites in Fig. 3. In the figure, each site's hourly average wind speed values are normalized to the respective monthly mean wind speed. A strong diurnal correlation is seen, with a consistent 20% nighttime enhancement and corresponding 20% daytime reduction in wind speed throughout the region. There appears to be no seasonal component to this trend, with the exception being a springtime deviation at the Sand Mt and Indian Mt sites.

6.6. Wind direction

Wind roses weighted by both time and energy are shown for seven sites in Fig. 4. The prevailing wind direction is out of the west and northwest. Many sites also show a SE component, likely from fronts of a coastal origin, and a SW component, most likely due to springtime storm systems originating in the Gulf of Mexico.

7. Wind development potential and summary

The southern Appalachian Mountains contain an abundant and verified wind resource. Annual average wind speeds have been found to be between 5.5 and 7.4 m/s, with the highest wind speeds on the ridge tops along the TN–NC border. Based on an informal survey of the regional wind map, there are an estimated 1600 km of ridge top with a power density exceeding 400 W/m^2 at 65 m along the Appalachian Mountain chain, with an additional 200 km of such ridge top on the Cumberland Plateau. Turbulence appears to be moderate, averaging 0.17, and wind shear coefficients are quite high, around 0.25.

Table 5
Annual energy output in MkWh and capacity factor estimates

Site	AEO (MkWh)	CF (%)
Black Mt, KY*	39.5	18
Bryson Mt, TN	61.9	28
Buffalo Mt, TN*	61.9	28
Cross Mt, TN	53.0	24
Forge Mt, TN	52.5	24
Howard's Knob, NC	74.5	34
Indian Mt, VA	62.8	29
Sand Mt, GA*	23.1	11
Stone Mt, TN	78.7	36

*The shape parameter is not known, so $k = 2$ is assumed.

Appalachian ridges tend to run SW–NE, which is perpendicular to the prevailing wind direction. Wind projects will likely be linear in extent along the ridge top and relatively small. However, in the Cumberland Plateau region interconnected ridges allow the possibility of larger projects. Further, the Cumberland Plateau has been extensively strip mined for coal. Wind development in this region would provide a revenue stream from land of little value.

Estimated annual energy output from a wind farm consisting of 15 GE 1.5 MW SL turbines is shown in Table 5, along with a calculated capacity factor, which is the ratio of the actual energy production to the theoretical maximum energy production. To perform these calculations, an annual wind speed distribution is created from each site's measured Weibull parameters, and a 10% derating of energy output is assumed. The better sites have predicted capacity factors approaching 35%.

A winter nighttime peaking of energy production matches well with the regional electrical load profile. Electric heat is common in the Southeastern US, so winter nighttime generating capacity will be an effective peak load shaving component to the region's energy portfolio.

Opinion surveys conducted in the Southeast clearly indicate widespread popular support for utility-scale wind projects in the. For example, a 2002 survey in western NC reports that 75% of respondents support wind development in the region, with over 60% in favor of turbines placed on the ridge tops [16]. A survey conducted for the TVA indicates that over 90% of respondents prefer wind power over other new generation options [17].

Obstacles to wind project development in the region include low electricity rates, high development costs due to terrain, high easement costs as some ridge top land is valued for residential development, and a diseconomies of scale. In 1983 the NC General Assembly enacted the Mountain Ridge Protection Act (G.S. 133A-205) to prevent structures exceeding 35 ft in height from being erected along ridge tops above 3000 ft. The law was passed in response to a large ridge top condominium and has an exemption for "wind mills", but has effectively discouraged developers from considering NC.

The region has historically lacked effective State incentives to encourage large-scale wind development, but this is changing. Tennessee and NC have voluntary consumer green power programs. North Carolina has a Renewables Portfolio Standard (12.5% by 2020). Virginia, TN, and NC have corporate tax credits or property tax exemptions.

Operating issues associated with a regional wind project include rime ice and lightening strikes (experienced at Buffalo

Mt and anemometer sites) and stresses caused by the large wind shear. Bat mortality at Buffalo Mt and at the Mountaineer wind project in nearby West Virginia has been above the national average. However, the vast majority of the mortality occurs during a 3-week period in late summer when the wind resource is very low. Keeping the turbines off line at night during this time should help to mitigate this problem.

Acknowledgement

This analysis was performed under Contract #51906 for the Tennessee Valley Authority.

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